REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 17/06/2005

2. REPORT TYPE: FINAL

3. DATES COVERED *(From - To)*: 01/01/03-12/31/04

4. TITLE AND SUBTITLE: Finescale Structure of the Temperature-Salinity Relationship

5a. CONTRACT NUMBER:

5b. GRANT NUMBER: N00014-03-1-0356

5c. PROGRAM ELEMENT NUMBER:

5d. PROJECT NUMBER: WHOI 13335600

5e. TASK NUMBER:

5f. WORK UNIT NUMBER:

6. AUTHOR(S)
PI Kurt L. Polzin - WHOI
Co-PI Raffaele Ferrari - MIT

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
MS #21 Department of Physical Oceanography
Woods Hole, MA 02543

8. PERFORMING ORGANIZATION REPORT NUMBER: FINAL

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S): ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S):

12. DISTRIBUTION/AVAILABILITY STATEMENT
UNLIMITED DISTRIBUTION - UNCLASSIFIED

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The establishment of the temperature-salinity (T-S) relationship in the ocean is the result of T-S variability generated at the surface by air-sea fluxes and its removal in the interior by molecular dissipation. The cascade of T-S variance to molecular scales results from advection by the large scale circulation, isopycnal stirring by mesoscale eddies, and diapycnal mixing by microscale turbulent processes. Advection brings different water masses in contact; isopycnal stirring enhances T-S gradients along isopycnals and diapycnal mixing sets the rate at which mean gradients and gradients resulting from isopycnal stirring are mixed together. Measurements of thermal dissipations from two recent field programs, NATRE and SFTRE, were analyzed to quantify the relative importance of eddy stirring and turbulent mixing in driving water mass conversion.

The result of this analysis is relevant to the study of propagation of acoustic signals in the oceanic environment. Acoustic scattering is a product of sound speed anomalies associated with T-S finestructure and is extremely sensitive to the spectral distribution of such finestructure. In this work we have shown that eddy stirring sets the rate of creation of finestructure. Thus parameterizations of mesoscale processes are needed to predict the spectral distribution of finescale structure.

15. SUBJECT TERMS
Temperature, salinity, acoustic signals, T-S finestructure

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified			Unlimited	8	Kurt L. Polzin
					19b. TELEPHONE NUMBER *(Include area code)* 508-289-2534

Finescale Structure of the Temperature-Salinity Relationship

PI Kurt L. Polzin
Woods Hole Oceanographic Institution
MS #21
Woods Hole, MA 02543
Phone: (508) 289-3368 Fax: (508) 457-2181 Email: kpolzin@whoi.edu

Co-PI Raffaele Ferrari
54-1420
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139-4307 USA
Phone: (617) 253-1291 Fax: (617) 253-4464 Email: rferrari@mit.edu

Award Number: N00014-03-1-0354
http://mit.edu/raffaele/www/main.htm

LONG-TERM GOALS

The long term goal of this project is to understand the processes that establish the temperature-salinity relationship in the ocean, with emphasis on the interplay between advection at the large scale, eddy stirring at the mesoscale and turbulent mixing at the finescale.

OBJECTIVES

The objectives of this proposal are (1) to unfold the processes that participate in the creation of the temperature-salinity relationship in two high-resolution data sets, the North Atlantic Tracer Release Experiment (NATRE) and the Salt Finger Tracer Release Experiment (SFTRE), and (2) to determine the relative importance of eddy stirring and turbulent mixing in the ocean interior with a combination of numerical and theoretical tools.

APPROACH

The approach is foremost to analyze and interpret finescale phenomena in high resolution oceanographic data sets, and secondarily to develop simple analytic and numerical representations to explain those phenomena. The analysis of the observations was done in collaboration by Raffaele Ferrari and Kurt Polzin. Raffaele Ferrari, in collaboration with Shafer Smith (assistant professor at the New York University), has run numerical simulations configured to study the generation of T-S finestructure by eddy stirring.

Maxim Nikurachine, a student of the Joint Program between Woods Hole and MIT, worked under the supervision of Raffaele Ferrari to develop simple theoretical models of eddy stirring of passive tracers. This work provided the framework to interpret the generation of T-S finestructure.

WORK COMPLETED

We completed the analysis of the temperature variance and eddy kinetic energy budgets for the North Atlantic Tracer Release Experiment (NATRE) in the Eastern North Atlantic and Salt Fingering Tracer Release Experiment (SFTRE) in the Western North Atlantic. The analysis was based on an extension of the Oborn-Cox model to account for the production of finescale temperature variance by mesoscale eddy stirring. Results for the NATRE region are reported in a manuscript accepted for publication in the Journal of Physical Oceanography. Results from the SFTRE region have been submitted for publication in Science. A third manuscript, to be submitted to the Journal of Physical Oceanography, focuses on the dynamics that link isopycnal stirring to molecular dissipation and their role in setting the T-S relationship in the NATRE and SFTRE regions. Finally we are completing a numerical study of the effect of eddy stirring on water mass transformations and on the T-S relationship of the global oceans; the results will be reported in a fourth manuscript.

As part of this proposal we also investigated the role of vortical modes (manuscript published in the Journal of Physical Oceanography) and internal waves (manuscript in preparation for the Journal of Physical Oceanography) in creating finescale structure along density surfaces.

RESULTS

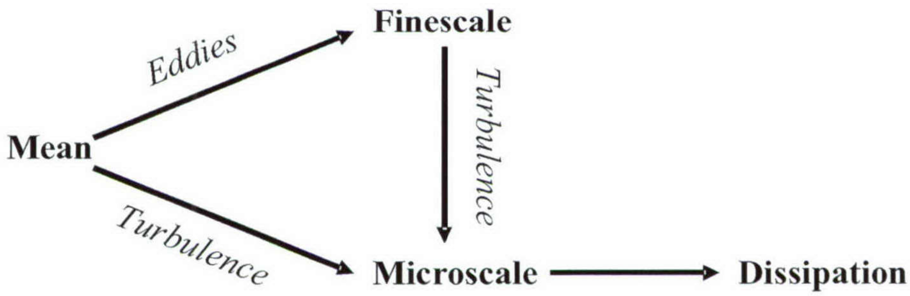
The establishment of the temperature-salinity (T-S) relationship in the ocean is the result of T-S variability generated at the surface by air-sea fluxes and its removal in the interior by molecular dissipation. The cascade of T-S variance to molecular scales results from advection by the large scale circulation, isopycnal stirring by mesoscale eddies, and diapycnal mixing by microscale turbulent processes. Advection brings different water masses in contact; isopycnal stirring and diapycnal mixing set the rate at which the water masses are mixed together. Measurements of thermal dissipations from two recent field programs, NATRE and SFTRE, were analyzed to quantify the relative importance of eddy stirring and turbulent mixing in driving water mass conversion.

The NATRE and SFTRE observational programs included fine- and micro-scale measurements and provided snapshots of T-S variability across an unprecedented range of scales, from basin to molecular. Such a wide range of scales was key to this project, because isopycnal stirring by mesoscale eddies acts on scales of 10-100 km and turbulent mixing is only effective on scales shorter than 100 m. Traditionally the interpretation of microstructure measurements is based on the model of Osborn-Cox. The model assumes that dissipation of thermal variance is due to turbulent motions acting on the mean temperature stratification, with no contribution from eddy stirring. The model assumes the following path for temperature variance,

Osborn-Cox model

Eddy processes are typically neglected because of lack of measurements at the mesoscale, rather than because of sound physical arguments. Notice that in our notation turbulence includes all microscale physics from wave breaking due to vertical shears to double diffusive instabilities.

In our work we extended the Osborn-Cox model to include the variance production by isopycnal eddy stirring, using a triple decomposition scheme (Davis 1994, Garrett 2001). The revised model shows that variance at the microscale can be generated by eddy stirring acting on the mean T-S profiles, creating finestructure, which is eventually removed by turbulence,



Triple decomposition model

Eddy stirring and turbulent mixing act very differently on temperature T-S distributions. Turbulence drives fluxes both along and across density surfaces, while mesoscale eddy motions are directed along density surfaces (isopycnals). In regions where temperature variance production is dominated by turbulence acting on the mean stratification, one expects to find smooth T-S profiles with wiggles at the microscale. In regions where temperature variance production is dominated by eddy stirring, one expects T-S profiles to exhibit structure at the finescale along isopycnals.

This paradigm was used to analyze microstructure measurements from NATRE and SFTRE. In the thermocline waters (upper 800 m), we found that turbulent mixing dominates and the T-S profiles show little variability along isopycnals. At these levels, turbulence is predominantly in the form of internal wave breaking in NATRE, while double-diffusive fingering dominates the turbulent variance production in SFTRE. In contrast, in the less stratified waters below the thermocline (between 800 and 1600 m), the T-S relationship exhibits a large degree of variability along isopycnals. This variability takes the form of sharp compensated T-S gradients, i.e. isopycnal T-S gradients, with little signature in density. Compensated variability is generated by mesoscale eddy stirring acting on climatological water mass contrasts along density surfaces.

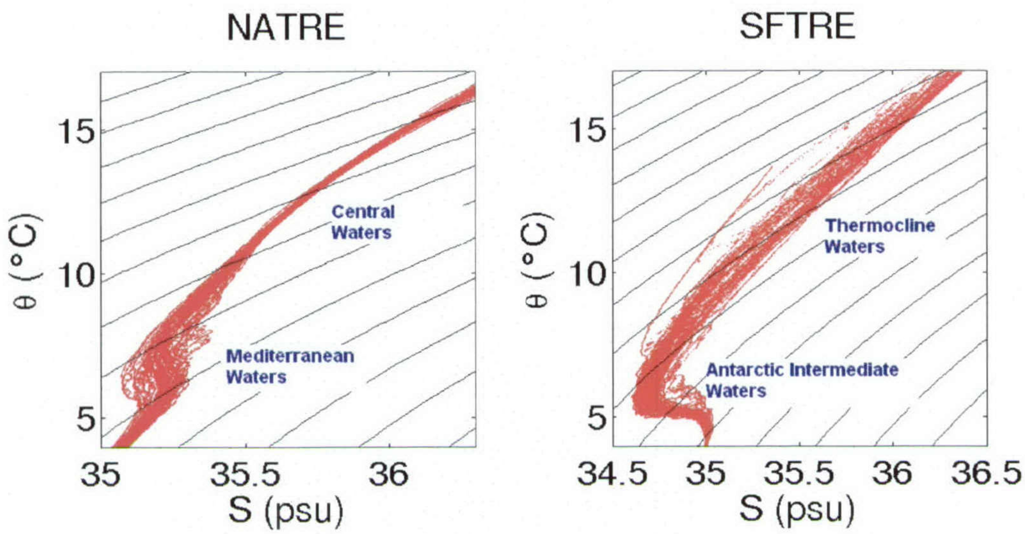


Figure 1: T-S relationship in the NATRE and SFTRE regions.

This interpretation of eddy stirring producing finestructure along isopycnals is confirmed quantitatively by the temperature variance budget analysis of the two data sets. Results from the NATRE data set are shown in Figure 2. Microstructure estimates of temperature variance dissipation for each layer are shown in red and the shaded boxes represent the error bars. The production of variance by turbulent motions acting on the mean vertical gradient is shown in black. The production of variance by eddy stirring of the mean isopycnal gradient is represented in blue. At the North Atlantic Central Water level, temperature variance production is associated with turbulence acting on the mean diapycnal temperature gradient, i.e. variance follows the lower branch of the triple decomposition model. At the Mediterranean Water level, eddy stirring dominates to the production of temperature gradient variance, i.e. variance follows the upper branch of the triple decomposition model.

Figure 3 shows the analysis for the SFTRE data set; the color scheme is the same used in Figure 2. In the upper 800 m turbulent mixing dominates the production of temperature variance, while eddy stirring is subdominant. Notice though that eddy stirring still accounts for 25% of the total dissipation. At the same levels, eddy stirring is much smaller in NATRE. At the SFTRE site, eddies generate T-S variability by stirring the isopycnal T-S contrasts between Subtropical Underwater and South Atlantic Thermocline Water. There are no equivalent T-S gradients along isopycnals in the Central Waters of the Eastern Atlantic. Another major difference between the two data sets at these levels is that the turbulent production of thermal variance is dominated by double diffusive fingering in SFTRE. The effect of salt fingers is evident in the staircases apparent in many of the vertical T-S profiles. Most importantly, salt fingers produce large turbulent fluxes and enhanced diapycnal diffusivities: turbulent thermal diffusivities are close to 0.5×10^{-4} m^2/s in SFTRE, compared to 0.08×10^{-4} m^2/s in NATRE. Below the thermocline, where stratification is weaker, turbulent mixing acting on the mean vertical gradient of temperature becomes less efficient and eddy stirring dominates the production of thermal variance.

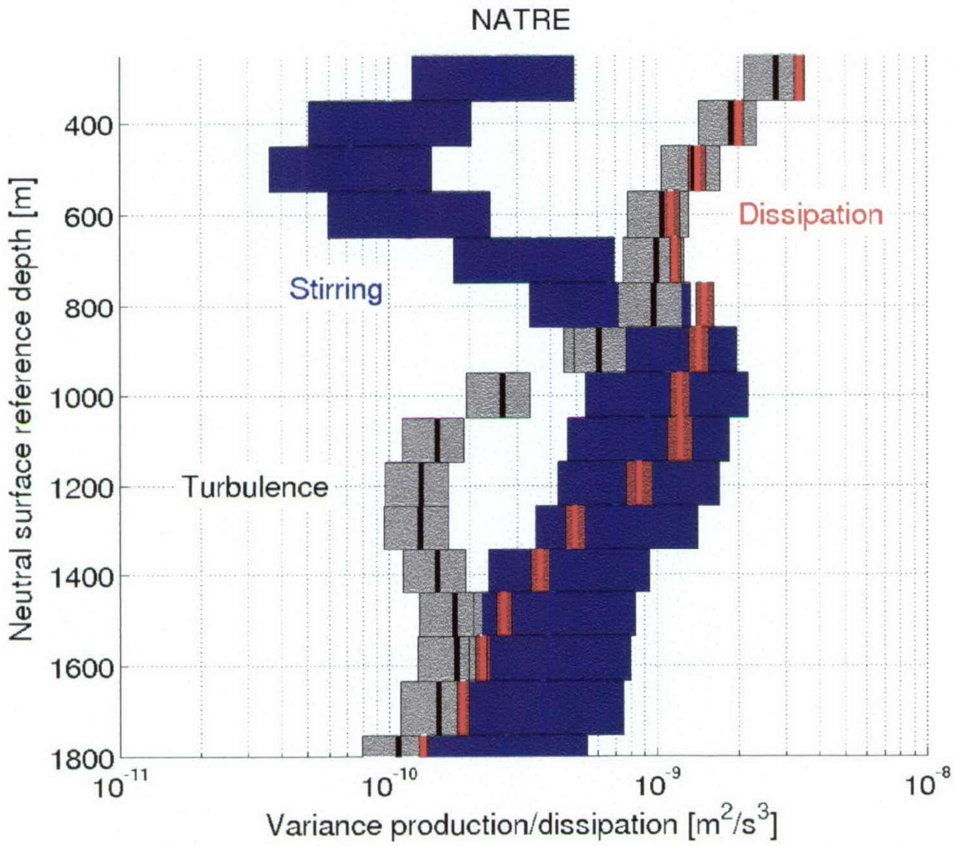


Figure 2: Temperature variance budget in the Eastern North Atlantic. The blue and black lines represent thermal variance production by eddy stirring and turbulence, respectively. The red lines represent thermal dissipation χ.

A main result of this analysis is that eddy stirring contributes substantially to the generation of temperature variance at the microscale across water mass fronts, where there are T-S gradients along isopycnals. The resulting finestructure is characterized by compensating T-S gradients, i.e. T-S gradients with no signature on density. This process is most efficient below the thermocline waters, where the weak stratification reduces the efficiency of thermal production by turbulent processes acting on the mean gradients. The generation of isopycnal gradients cannot proceed without limit and must be arrested by some mixing mechanism at the microscale. Garrett (1982) speculated that the compensated gradients might become unstable to double diffusive instabilities at small scales which would limit further growth of the gradients. Microstructure data do not confirm this scenario: isopycnal gradients are arrested by shear insatbilities at low Richardson number.

In order to support our interpretation of the data, we used a quasi-geostrophic model to study the generation of isopycnal T-S gradients through eddy stirring. The main question we wanted to answer is whether the oceanic velocity field, which is dominated by low modes with little vertical structure, can generate the sharp T-S gradients found in NATRE and SFTRE. Numerical simulations show that the combination of lateral straining and vertical shear in the eddy field are very efficient at generating vertical gradients in temperature and salinity. In Figure 4, we show a striking example of the difference in spatial variability between temperature and velocity (shown as a stremfucntion) in a rich eddy field representative of the conditions found in NATRE. The rich filamentation in temperature is associated with large vertical gradients much alike in the NATRE data set, even though the velocity field has little horizontal and vertical structure.

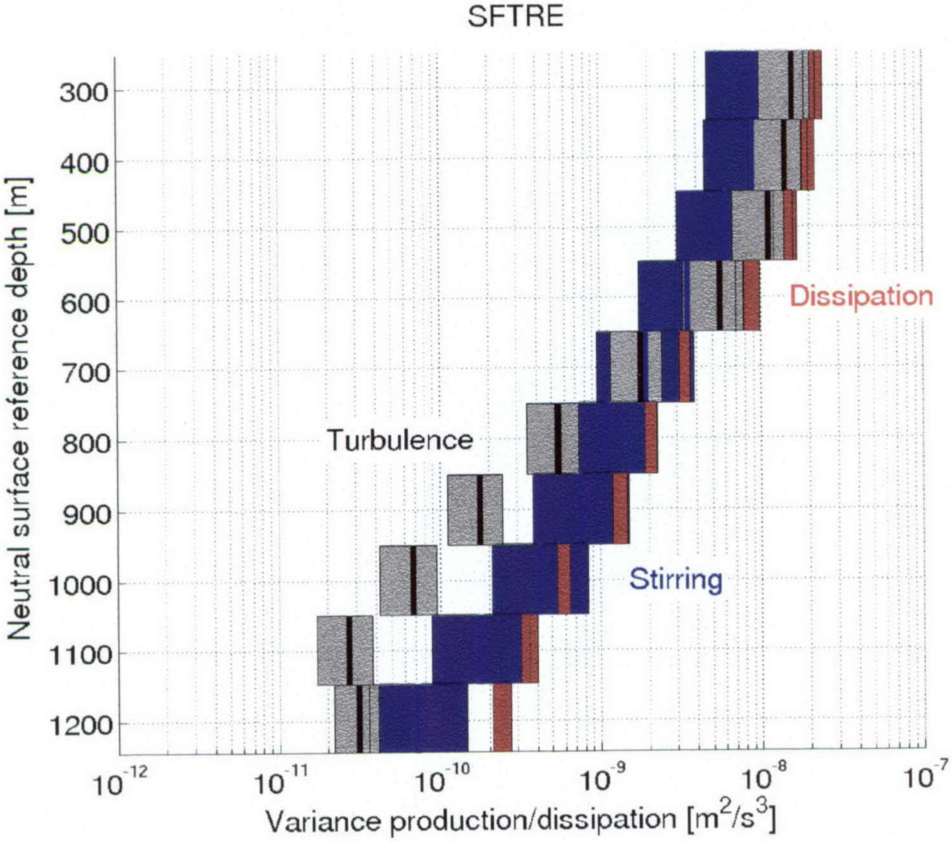


Figure 3: Temperature variance budget in the Western North Atlantic. The blue and black lines represent thermal variance production by eddy stirring and turbulence, respectively. The red lines represent thermal dissipation χ. Turbulence includes both shear instabilities and double diffusive fluxes.

IMPACT/APPLICATIONS

We anticipate that this work will form the basis for future interpretation of microstructure data and for the parameterization of the interplay of mesoscale eddy stirring and double diffusive turbulence. Furthermore, our results suggest that water mass conversion below the thermocline is controlled by mesoscale eddy stirring. Thus ocean models cannot reproduce the T-S relationship found in the real ocean, if appropriate parameterizations for eddy stirring are not included. The common practice of representing eddy stirring with a constant isopycnal diffusivity is not satisfactory: such a closure is not consistent with the NATRE and SFTRE observations.

The result of this analysis is relevant to the study of propagation of acoustic signals in the oceanic environment. Acoustic scattering is a product of sound speed anomalies associated with T-S finestructure and is extremely sensitive to the spectral distribution of such finestructure. In this work we have shown that eddy stirring sets the rate of creation of finestructure. Thus parameterizations of mesoscale processes are needed to predict the spectral distribution of finescale structure.

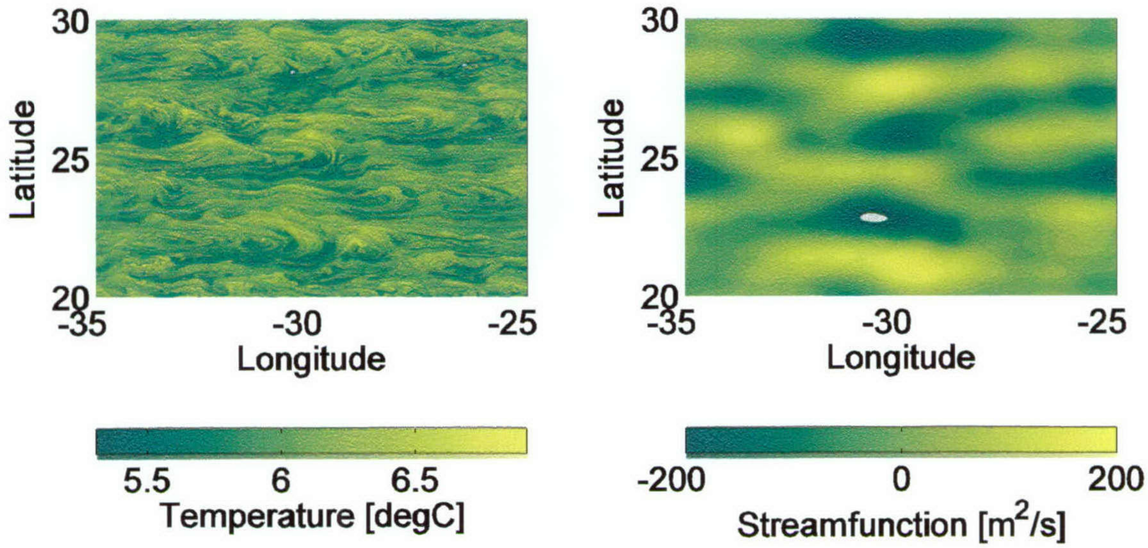


Figure 4: Temperature (left panel) and streamfunction (right panel) along an isopycnal surface from a quasi-geostrophic model of the Eastern North Atlantic.

TRANSITIONS

Ocean circulation models are extremely sensitive to the rate of isopycnal stirring and diapycnal mixing. Thus the predictive ability of ocean models depends upon the parameterization of finestructure phenomena. The description of finestructure and physical understanding provided by our simple analysis provides a useful benchmark to test model skill.

RELATED PROJECTS

J. Ledwell, J. Toole and R. Schmitt were leading PIs in the NATRE and SFTRE experiments. The insight gained as part of this grant will have a direct impact on the interpretation and comparison of microstructure data and tracer release measurements.

REFERENCES

Davis R., 1994. Diapycnal mixing in the ocean: The Osborn-Cox mode, *Journal of Physical Oceanography*, **16**, 1847-2576.

Garrett, C., 1982. On the parameterization of diapycnal fluxes due to double diffusive intrusions, *Journal of Physical Oceanography*, **12**, 952--959.

Garrett C., 2001. Stirring and mixing: what are the rate controlling processes?, *Proceedings of the Aha Huliko`a Winter Workshop*, P. Müller and D. Henderson Editors, 1-8.

PUBLICATIONS

Polzin K. L, and R. Ferrari, 2004. Isopycnal Dispersion in NATRE, *Journal of Physical Oceanography,* **34**, 247-257 [published, refereed].

Ferrari R., and K. L. Polzin, 2004. Temperature and Salinity Finestructure in NATRE, *Journal of Physical Oceanography* [accepted, refereed].

Schmitt R. W., J. R. Ledwell, E. T. Montgomery K. L. Polzin, and J. M. Toole, 2004. Enhanced Diapycnal Mixing by Salt Fingers in the Thermocline of the Tropical Atlantic, *Science* [submitted, refereed].

Ferrari R., and Y. Lvov, Dispersion of passive tracers by internal waves, in preparation for *Journal of Physical Oceanography* [to be submitted, refereed].

Ferrari R., and K. L. Polzin, Isopycnal Eddy Stirring, Double Diffusion, and the Temperature and Salinity Finestructure in SFTRE, in preparation for *Journal of Physical Oceanography* [to be submitted, refereed].

Ferrari R., and S. Smith, Eddy Stirring and the Generation of Thermohaline Finestructure, in preparation for *Journal of Physical Oceanography* [to be submitted, refereed].

HONORS/AWARDS/PRIZES

Raffaele Ferrari, Victor P. Starr Career Development Professorship, Massachusetts Institute of Technology.

Kurt Polzin, European Geophysical Society's Fridtjof Nansen Medal.